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ISIS-A SPACECRAFT MAGNETIC TESTS

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GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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J. C. Boyle
Test and Evaluation Division
Systems Reliability Directorate

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GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

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MAGNETIC TESTS

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PROJECT STATUS

This is the final report of the magnetic moment determination and reduction on the ISIS-A spacecraft. After leaving the Magnetic Test Facility the spacecraft was given a final checkout for weight, center of gravity, and moment of inertia. The spacecraft was then shipped to the Western Test Range and successfully launched on January 30, 1969.

AUTHORIZATION

Test and Evaluation Charge No. 325-872-11-26-01

ISIS-A SPACECRAFT MAGNETIC TESTS

J. C. Boyle
Test and Evaluation Division

SUMMARY

The ISIS-A spacecraft was tested in the GSFC Attitude Control Test Facility. An initial series of tests took place August 23-30, 1968 and a final series November 22-27, 1968.

In the initial series of tests the spacecraft, as received, had a perm moment of 388 pole cm which was reduced by deperm treatment to a final value of 203 pole cm. A maximum moment of 578 pole cm occurred during stray power testing. The maximum induced moment was 356 pole cm, when a field of 0.3 gauss was applied +x direction. The magnetic moment of the torquing coils was measured both by magnetometer and torquemeter to be about 140,000 pole cm both statically and dynamically. Gating thresholds and sense of moment were proper. In addition all on-board magnetometers were satisfactorily calibrated.

In the final series of tests the perm moment as received was 3295 pole cm, mostly along the z axis. This was reduced by deperm treatment to 681 pole cm as a final value. Rechecks were made of the spin and attitude control system as well as final calibration of the magnetometers. All results fell within the specification limits.

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ISIS-A SPACECRAFT MAGNETIC TESTS

INTRODUCTION

The ISIS-A spacecraft is to be spin stabilized. The spin rate is to be a nominal 3 rpm and is to be controlled by torque produced by interaction between the terrestrial magnetic field and the magnetic moment generated by on-board toroidal air-cored coils. In addition, the spin-axis attitude is also to be controllable, using the same on-board coils but in a different control mode. A magnetometer aligned normal to the spin axis is used in spin-rate control. A magnetometer parallel to the spin axis is used in conjunction with solar sensors in controlling spin-axis attitude.

Six magnetometer probes are on-board. Four of these are associated with experiments and two with spin and attitude control as previously mentioned.

The spin and attitude control system is required to be capable of changing spin at a maximum rate of 0.1 rpm per orbit (2 hours) and to change spin axis inclination at a maximum rate of 3 degrees per orbit. This requires the air cored torque coils to be capable of producing a magnetic moment of about 150,000 pole centimeters. Whenever the magnetic field component associated with a control mode exceeds approximately 100 milli-oersteds, the torque coils are to be gated on to the full 150,000 pole centimeters. Conversely, when the field drops below 100 milli-oersteds, the torque coils are to be gated off.

PURPOSE

The objectives of the tests were as follows:

1. To determine the permanent, induced and stray magnetic moments of the spacecraft and to assess its magnetic stability.

2. To evaluate the spin and attitude control system.

3. To calibrate the six magnetometer probes on-board the spacecraft and to determine the effects of the spacecraft permanent, induced and stray magnetic fields at these probes.

4. To deperm compensate, and make any other adjustments necessary to achieve satisfactory magnetic characteristics for the spacecraft.

TEST DESCRIPTION

Set-Up

The tests were conducted in the GSFC Attitude Control Test Facility. This facility utilizes a 40 foot dia Braunbek coil system to produce a controlled magnetic field of high uniformity over a large central volume. The facility is described in Appendix A.

The ISIS-A spacecraft was mounted on the turntable-dolly with the 9 foot dia deperm coil in place. The orientation of the spacecraft was such that its + x axis was directed north, its + y axis was directed east and its + z axis directed up. This orientation conforms to the GSFC convention except for the z axis whose positive direction is opposite.

Magnetic measurements were made at four locations using Forster Hoover Model MF 5050 tri-axial probes. The locations of these probes were as shown on Figure 1. Note that Probe No. 2 located to the east of the spacecraft was relocated from 6 feet to 17 feet during the magnetic moment portion of the torque coil testing sequence. The signals from the probes were hard-wired to the Operations and Instrumentation Building for monitoring. The signals were displayed as meter indications, as analog traces on Brush recorders and as digital computer print-outs (MADAS). The meter readings and analog traces were used for real time quick look monitoring, the MADAS print-out not being immediately available. The final calculations which appear in this report are based on the MADAS print-outs.

Procedure

Initial magnetic tests were performed on the ISIS-A spacecraft in August 1968. These consisted of:

1. Initial moment measurement
2. 15 Gauss exposure
3. Deperm by dc rotation from 50 gauss maximum
4. Measurement of torquer coil feedback to magnetometer probes
5. Measurement of initial probe bias due to permanent moment.
6. Magnet compensation

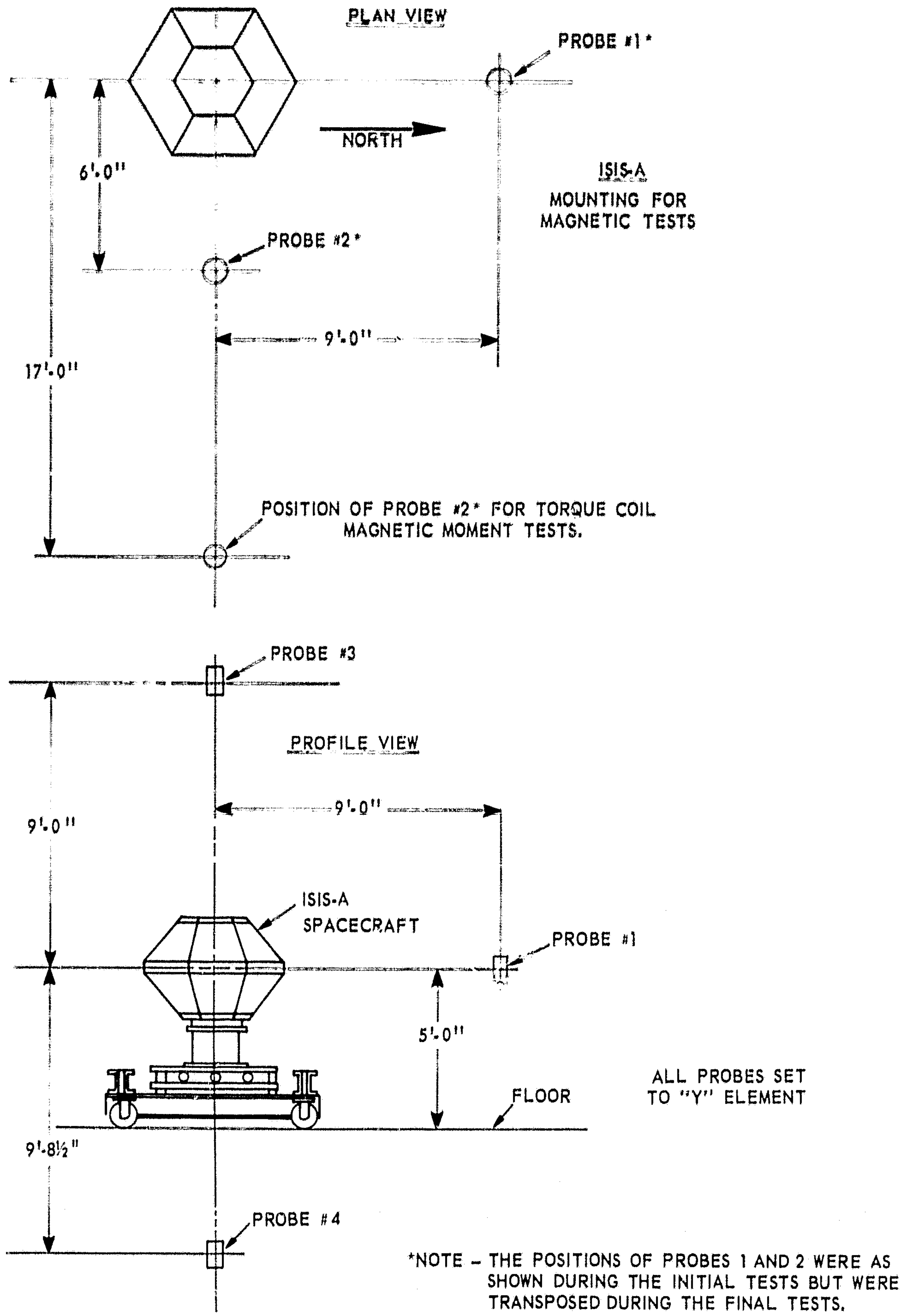


Figure 1. ISIS-A Mounting for Spacecraft Tests

7. Torquer coil turn on/off threshold determination

8. Induced magnetic moment measurement

9. Stray field magnetic moment measurement

10. Magnetometer calibration (x and y sensors)

11. Torque test of torquer coils

12. Magnetometer calibration (z sensors)

Final magnetic tests were performed in November 1968 and consisted of:

1. Recheck of perm moment

2. Deperm by dc rotation from 50 gauss maximum

3. Probe bias measurement

4. Torquer coil feedback measurement

5. Induced magnetic moment measurement

6. Torquer coil threshold measurement

The details of the procedures followed in carrying out these tests and the computational techniques used are summarized in Appendix B.

INITIAL TEST

Results and Discussion

Magnetic Moment — The magnetic moment history of the spacecraft as determined from magnetic field measurements appears in Table 1. The measured moments are seen to be well within the nominal values considered acceptable.

Torquer Coil Moment — The results of the torquemeter measurements of torquer coil moment appear in Table 2. It is app .rent that torquemeter measurements and magnetic measurements taken under static field condition are in good agreement. The moment produced by the torquer coils is approximately 140,000 pole cen .meters as compared to the nominal value of 150.000 pole centimeters.

Table 1

Magnetic Moments — Initial Tests

Magnetic State	Moment Orientation (Degrees cw From +x Direction)	Moment Magnitude (Pole cm)		
		M_{xy}	M_z	M_{total}
Initial Perm	80	384	-55	388
Post 15 Gauss Exposure	80	699	-99	706
Post Deperm	230	305	45	308
Torque Coil On	270	141,000	—	141,000
Post Torque Coil Operation	250	282	73	292
Induced (0.3 Gauss In +x Direct.)	0	350	—	350
Post Induced	270	289	49	293
Perm + Stray	110	511	-271	578
Final Perm	270	200	37	203

Note: All values listed are with respect to the spacecraft axes.

The perm moment of the spacecraft was difficult to measure as the signal to noise ratio was unfavorable. The resonating technique was used, the result being an M_{xy} of 438 pole cm as compared with 200 pole cm obtained by magnetic measurement.

<u>Compensation</u> — The perm moment of the spacecraft was sufficiently within bounds that no compensation was necessary. A small compensating magnet of about 1 pole cm was added to the S 600 probe to make the probe bias acceptable.

<u>Flight Magnetometers</u> — Tests were run to measure magnetometer probe bias, magnetometer system hysteresis, magnetic feedback from the torquing coils, hysteresis widths and threshold switching levels. This information was

Table 2

Torquemeter Test — Initial Tests

Control Mode	Applied Field			Torque		Magnetic Moment (Pole cm)
	Freq. Rad/Sec	Amplitude Gammas	Direction	Amplitude (Dyne. cm)	Direction	
Spin Up	0	30,000	+x	43,300	CCW	144,000
Spin Down	0	30,000	+x	41,000	CW	137,000
Spin Down	0.4	30,000	CW	25,000*	CW	137,000
Spin Up	0.4	30,000	CW	25,000*	CCW	139,000
Spin Up	0.2	30,000	CW	26,150*	CCW	143,500
Spin Down	0.2	30,000	CW	25,550*	CW	142,000
	Spacecraft Perm Moment					
Off	.250	60,000	N-S	192	OSC.	M_y = -320
Off	.250	60,000	E-W	179	OSC.	M_x = -298

*Average Value

collected directly by the project via telemetry from the spacecraft and is reported out in RCA-Victor Co., Ltd., internal memo from J. R. C. Cox to J. M. Stewart of 31 October, 1968; File No. 91650-55.

Problems

During one of the tests of the attitude control system it was noted that the torquer coils remained on in zero field. This was ascribed to insufficient bias voltage in the magnetometer electronics and was to be corrected by the project.

A small perm bias change was noted on probe z 600. This was found to be due to the presence of a steel ring in a nearby connector. This was to be replaced subsequent to the initial test phase.

Due to difficulties experienced in generating a z axis field with the 40 foot coil system it was decided to tip the spacecraft over on its own steel dolly to check attitude control threshold levels and to calibrate the z axis magnetometer. Later on, the z axis artificial field was turned on and operated satisfactorily. Calibration was repeated.

FINAL TEST

Results and Discussion

Magnetic Moment — The magnetic moment history of the final test is shown in Table 3. These moments are higher than recorded during the initial tests. It is presumed that the spacecraft was exposed to a strong magnetic field in the interval between the initial and final tests. The final value of perm, while much higher than at the end of the initial testing phase is still within specification limits of 750 pole cm per component and 1500 pole cm total.

Spin Control System — Static fields were applied and magnetometer measurements were made at several levels of input voltage to the attitude control system

Table 3

Magnetic Moments — Final Tests

Magnetic State	Moment Orientation (Degrees CW From +x Direction)	Moment Magnitude (Pole cm)		
		M_{xy}	M_z	M_{total}
Initial Perm	241	306	-3280	3295
Post Deperm	43	383	-579	694
Induced (0.3 Gauss +x)	22	380	+90	391
Induced (0.3 Gauss - z)	250	217	-487	533
Final Perm	36	321	-600	681

Note: All values listed are with respect to the spacecraft axes.

electronics. From this the moment due to the torquer coils was calculated as:

Applied Field	Input Voltage	Mode	M_y (Torquer Coils)
10,000 gammas (−x)	19	Spin-Up	−97,100 pole cm
10,000 gammas (−x)	22	Spin-Up	−118,000 pole cm
10,000 gammas (−x)	26	Spin-Up	−146,000 pole cm
10,400 gammas (+x)	22	Spin-Down	−152,000 pole cm
10,400 gammas (−x)	22	Spin-Down	+125,000 pole cm

During the above tests the probe locations were as follows:

Probe No.	Location
1	17 feet east
2	9 feet north
3	9 feet up
4	9 feet down

Dynamic field tests of the spin-control system were also run with a field of 30,000 gammas rotating at 3 rpm in a clockwise direction. Both spin-up and spin-down modes were commanded. These tests confirmed proper direction of control torque. The scale which it was necessary to use on the strip chart records precluded accurate measurements of coil moment or triggering threshold values but the rough values obtainable were of the proper magnitude. Additional records were obtained by the project via telemetry link.

Magnetometer Calibration—A final calibration was made of the spacecraft magnetometers. Data were collected by the project by means of telemetry. Results were satisfactory.

Problems

As previously mentioned, the spacecraft had evidently been subjected to a strong field along its z axis sometime between the initial and final magnetic tests.

This created a difficult situation since it was not possible with available equipment to apply a deperming field along the z axis. After several attempts, a satisfactory level of perm was finally achieved by using a horizontal axis rotational deperm from an initial 39 gauss level combined with a constant 50,000 γ field applied along the z axis in opposition to the perm moment.

CONCLUSIONS

The spacecraft, after final deperm treatment, was within prescribed magnetic limits. The final perm moment was 681 pole centimeters as compared to a maximum acceptable value of 1500 pole cm.

The spin and attitude control system was operated in all its control modes. Proper threshold values for gating the torque coils were demonstrated as well as proper sense of the magnetic moment generated. The moment values achieved were slightly less than the design goals; approximately 140,000 pole centimeters vs. a goal of 150,000 pole cm.

The on-board magnetometers were satisfactorily calibrated.

ACKNOWLEDGEMENT

The magnetic testing of this spacecraft and the acquisition of all data presented were accomplished as a team effort by the personnel of the Magnetic Test Section.

REFERENCES

1. Environmental Test Plan for International Satellite for Ionospheric Studies (ISIS-A) numbered S-8-500 and dated September 22, 1967.

2. ISIS-A Environmental Test Specification for Spacecraft System Tests. Prepared by NASA/GSFC numbered S-320 ISIS-1 and dated June 15, 1968.

3. Environmental Test Procedure for ISIS-A Spacecraft. Prepared by RCA Victor Company, Ltd., Montreal, Canada and dated August 1968, number 1816529.

APPENDIX A

DESCRIPTION OF FACILITY

The Attitude Control Test Facility (ACTF) provides a controlled magnetic environment in which to carry out magnetic tests of spacecraft or spacecraft components. The 40 foot diameter, 3 axis coil system permits the establishment of zero field or of a field of any desired magnitude and direction with a maximum of 60,000 gamma per component. Current regulated power supplies provide stability of ± 1 gamma over a 24 hour period while the coil geometry provides uniformity of field within 0.6 gamma over a spherical volume of 3.2 foot radius. Three earth's field magnetometers and associated control systems provide automatic compensation for the daily variation of the earth's field.

In addition to the generation of static magnetic fields, the coil currents may be programmed so as to produce a resultant vector which will rotate about any desired axis through the center of the coil system at a maximum rate of 100 radians per second. The magnitude of the rotating vector has a maximum limit of 60,000 gamma.

The facility is also equipped with a 5000 pound capacity overhead hoist, a 2000 pound capacity hydroset for gentle handling of delicate spacecraft, a track system and dolly for transporting the spacecraft from the trucklock to the center of the coil system and a turntable at the coil center which is powered to rotate the spacecraft through 360 degrees while it is centered in the coil. The turntable is equipped with an angle encoder so that angular position and magnetic measurements may be synchronized. In addition a gimbal is available with which to produce rotation of the spacecraft about a horizontal axis.

Fields up to 50 gauss for perming and deperming the spacecraft along one axis can be provided by means of a portable helmholtz coil pair of 9 foot diameter. There is also available a 5 foot diameter coil for applying such fields along a second axis of the smaller spacecraft.

The facility is equipped with a highly sensitive torquemeter located directly below the turntable, which permits the direct measurement of torques resulting from the interaction between the magnetic moment of the spacecraft under test and the field produced by the coil system itself. The torquemeter can be rigged to accept loads to 5000 pounds and to measure torques to an accuracy of 50 dyne centimeters.

Four tri-axial fluxgate type magnetometers are available and may be used simultaneously to provide meter display, strip chart records or digital print-out

records. The positions of the magnetometer probes may be varied to suit the particular needs of the individual spacecraft or sub-system under test.

A photograph of a spacecraft under test in the facility is shown in Figure 2.

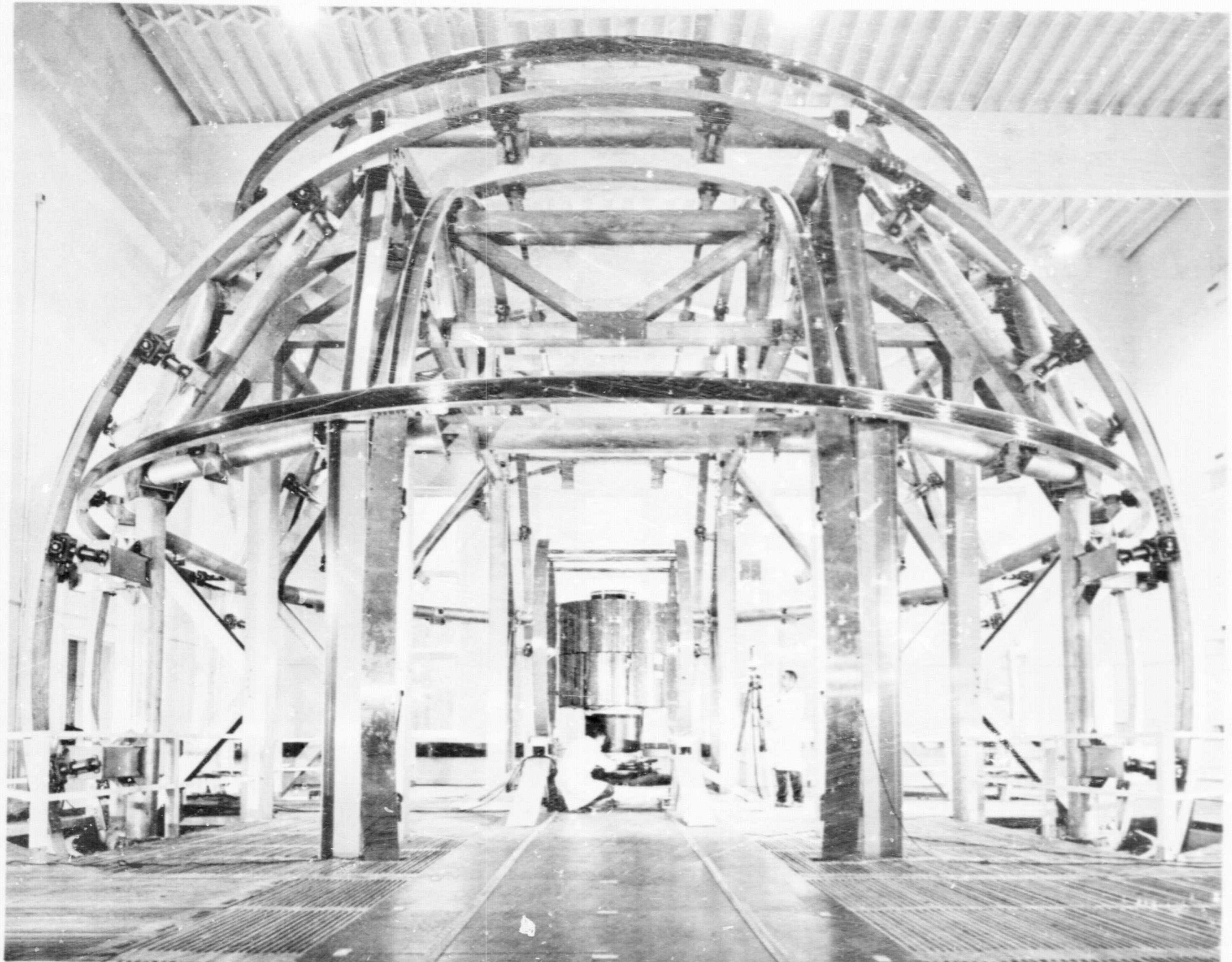


Figure 2. Spacecraft in the Attitude Control Test Facility

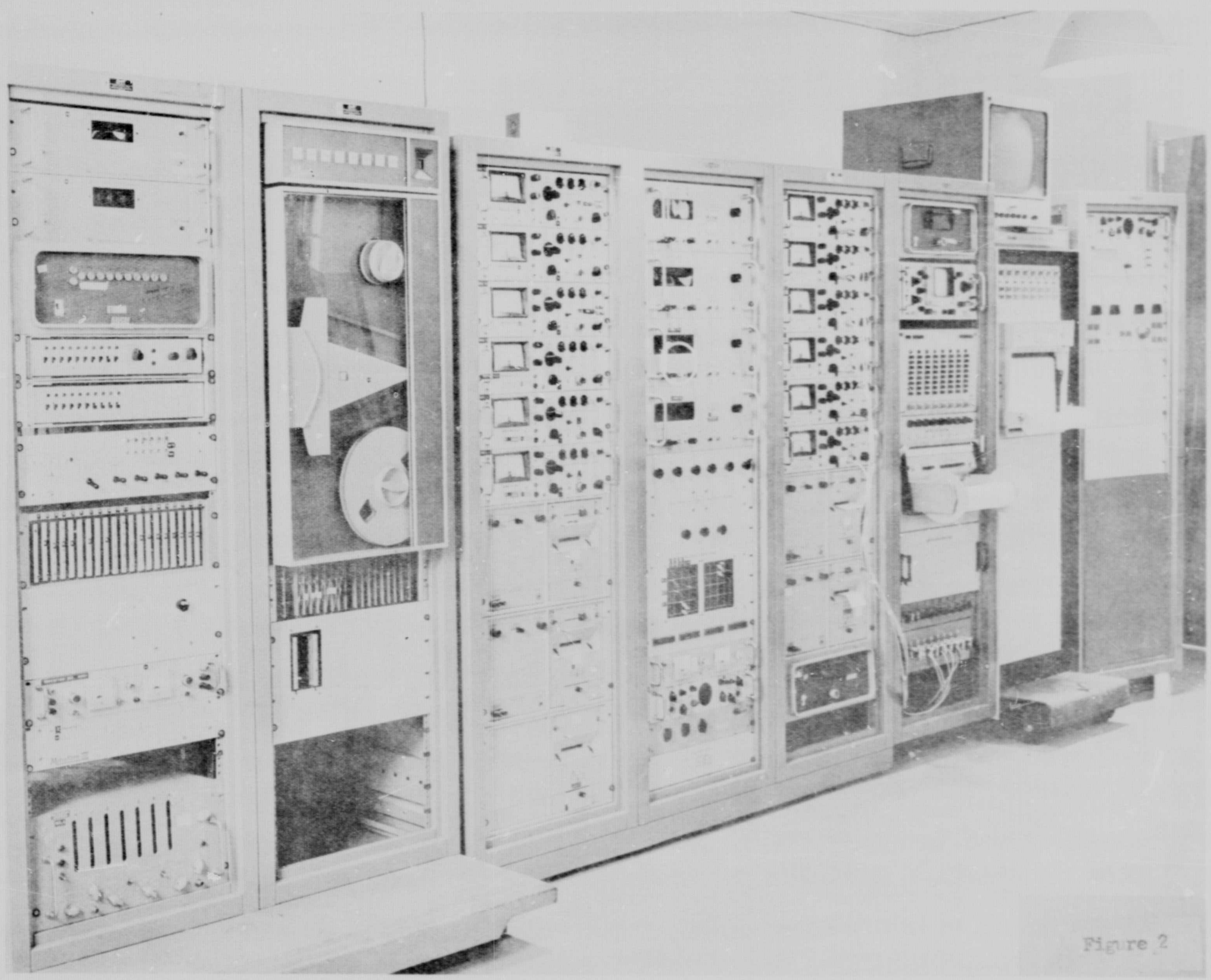


Figure 3. Recording Instrumentation for Magnetic Tests

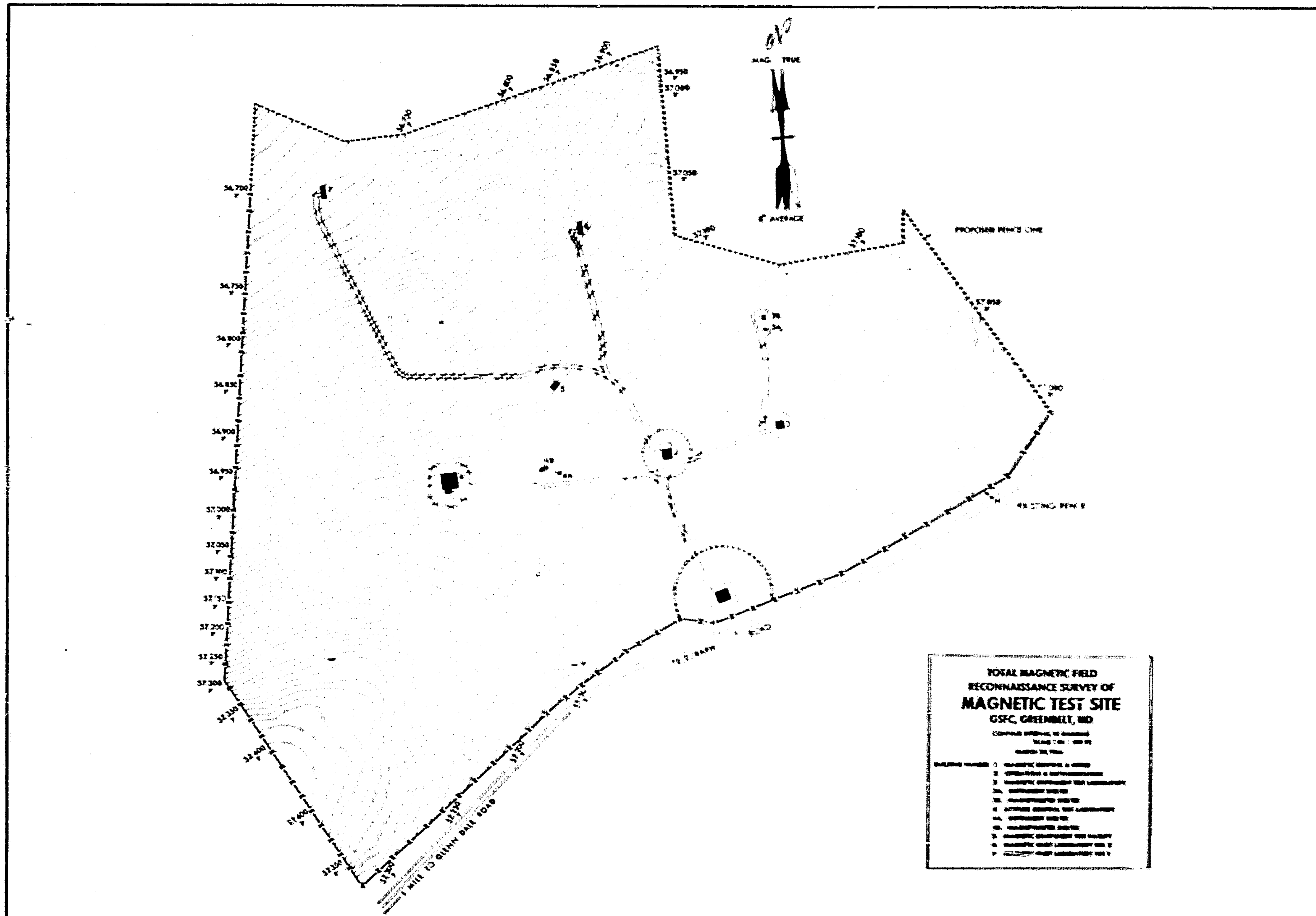


Figure 4. Total Magnetic Field Reconnaissance Survey of Magnetic Test Site

APPENDIX B

TEST PROCEDURES AND COMPUTATIONAL TECHNIQUES

DIPOLE MOMENT DETERMINATION

With the spacecraft in the truck lock, zero field is established at the center of the coil using the station Schoenstedt magnetometer. All four Forster Hoover probes are then adjusted to read zero. The spacecraft is next rolled in on the dolly into the center of the coil and rotated clockwise (as seen from above) through a complete revolution about the z axis.

Using the magnetic field data obtained during the above operations, the dipole moment components are calculated on the assumption that near field effects can be disregarded and that the measured field is due to a theoretical dipole. Under these circumstances

$$\bar{H} = \frac{2M \cos \phi}{r^3} \hat{r} + \frac{M \sin \phi}{r^3} \hat{\phi}$$

where

$\bar{H}$ = Magnetic field intensity vector

M = Magnetic dipole moment

r = Radial distance from dipole to point of measurement

ϕ = Angular displacement between dipole moment vector and radius vector

$\hat{r}$ = Unit vector in the direction of the radius

$\hat{\phi}$ = Unit vector tangential to the radius vector.

The Forster Hoover probes are located in line with the x, y and z axes of the facility. Therefore the x, y and z components of dipole moment produce either a radial field at $\phi = 0$ or a tangential field at $\phi = 90°$, on each of the four magnetometers.

The components of magnetic moment may be calculated from the fields measured at each of the probes when the spacecraft is rolled in.

For the magnetometer located to the north:

$$M_x = \frac{H_x\, r^3}{2}$$

$$M_y = -H_y\, r^3$$

$$M_z = -H_z\, r^3$$

For the magnetometer located to the east:

$$M_x = -H_x\, r^3$$

$$M_y = \frac{H_y\, r^3}{2}$$

$$M_z = -H_z\, r^3$$

For the magnetometers located above and below:

$$M_x = -H_x\, r^3$$

$$M_y = -H_y\, r^3$$

$$M_z = \frac{H_z\, r^3}{2}$$

When the spacecraft is rotated at the center of the coil system, a signature is obtained at each of the probes. If the probes are sufficiently far away that higher order multipoles make a negligible contribution to the field, the signatures from the x and y probes will be sinusoidal. The total moment in the x y plane may be calculated from the peak-to-peak reading as follows:

For the magnetometer located to the north

$$M_{xy} = \frac{(H_x)_{p-p}\ r^3}{4}$$

$$M_{xy} = \frac{(H_y)_{p-p}\ r^3}{2}$$

For the magnetometer located to the east

$$M_{xy} = \frac{(H_x)_{p-p}\ r^3}{2}$$

$$M_{xy} = \frac{(H_y)_{p-p}\ r^3}{4}$$

For the magnetometers located above and below

$$M_{xy} = \frac{(H_x)_{p-p}\ r^3}{2}$$

$$M_{xy} = \frac{(H_y)_{p-p}\ r^3}{2}$$

The angular orientation (θ) of M_{xy} is gotten by observation of the angular displacement of the spacecraft corresponding to the peak reading of a particular horizontal probe. For example, suppose a positive peak of the x component of the north magnetometer occurs at a 90 degree rotation. The +x axis of the spacecraft is then pointing east while M_{xy} is directed north. In this case θ, the angle measured clockwise from the +x axis of the spacecraft, is 270 degrees.

Thus we see that in-out and rotational data provide us, theoretically, with more than enough information to calculate the spacecraft moment. However, near field effects often appear in the signatures of probes close to the spacecraft. In addition, probes located farther away may see very weak fields and thus be difficult to read accurately. Having readings from a number of magnetometers

permits the use of judgement in selecting the data which will give the most accurate results.

Exposure

This is accomplished by energizing with dc the pair of 9 foot coils within which the spacecraft was centered. The current is adjusted to produce the desired field level of 15 gauss.

Deperm

Spacecraft deperming is usually done by energizing the 9 foot coils with 60 cycle ac; starting at a 50 gauss level and gradually diminishing to zero. In the case of ISIS-A this could not be done since the project had placed a limit on the rate of change of flux of 50 gauss per second. ISIS-A deperming was accomplished by rotating the spacecraft at 9.6 rpm within the 9 foot coils while slowly diminishing the field from 50 gauss to zero in a period of 90 seconds.

Magnetometer Calibration

With the spacecraft centered in the coil, the outputs of the flight magnetometers were compared with the strength of the field produced by the coil facility along each axis in turn.

Torquer Coil Magnetic Testing

Magnetic fields were produced by the facility to activate the torquer system. The threshold values for activation and turn-off were measured with both static and rotating fields. During this period the east probe was moved from 6 feet to 17 feet away to permit measurement of the dipole field of the torquer coils and to establish a value for dipole moment which could be compared with the value obtained during torque testing.

Torquemeter Tests

The Mk III torquemeter was used to determine perm moment of the spacecraft and to evaluate its altitude control system. To determine the perm moment, a known field is applied by means of the facility coil system and the corresponding spacecraft torque is measured. The magnetic moment is found from the relationship

$$\bar{L} = \bar{M} \times \bar{B}$$

where B is magnetic induction.

In terms of components,

$$L_{z_1} = M_x \cdot B_y$$

and

$$L_{z_2} = M_y \cdot B_x$$

From these relationships, M_x and M_y may be determined. M_z cannot be evaluated without tipping the spacecraft since the torquemeter is only capable of measuring torques about a vertical axis.

The accuracy of the above measurements can be improved by making use of the dynamic response characteristics of the torquemeter. If the impressed field is oscillated at the mechanical resonance of the torquemeter, the response can be magnified, the limit being imposed by the amount of damping present. Typically, the dynamic response is greater than the static by a factor of about 10.

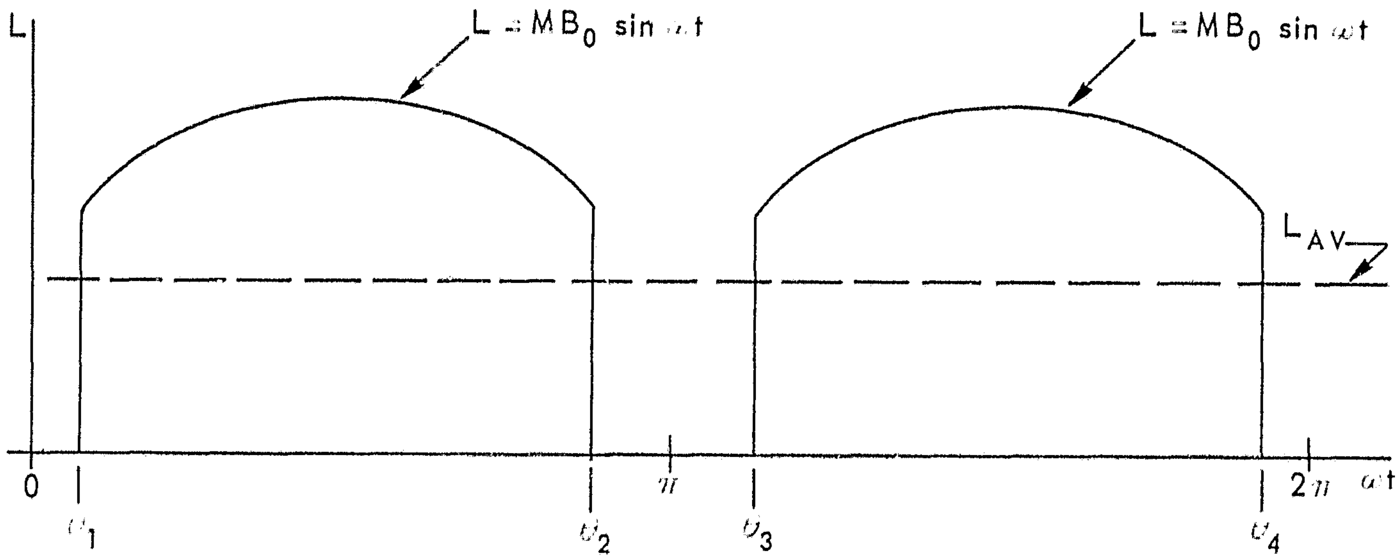
When the torquemeter is to be used to evaluate a spin-control system the impressed field is rotated at a rate corresponding to the spin rate of the spacecraft. When the spin control system is energized, the resulting torque is applied to the torquemeter.

The average value of the torquemeter's output is then equal to the average value of the spin control torque. While this is worthwhile information by itself, it is also possible to infer the torquer coil dynamic magnetic moment providing the energization thresholds and the rotating field are known. The following analysis serves to develop the concept:

With a magnetic field of strength B_0 rotating at an angular velocity ω, the torquer coil moment will interact with the quadrature component of the field to produce a torque equal to

$$L = M \times B_0 = MB_0 \sin \omega t$$

The control system gates and inverts the torquer coil moment to produce a pulsing output torque as shown



$$L_{AV} = \frac{\int_{\theta_1}^{\theta_2} MB_0 \sin \omega t \, d\omega t + \int_{\theta_3}^{\theta_4} -MB_0 \sin \omega t \, d\omega t}{2\pi}$$

$$2\pi L_{AV} = MB_0 \Big[-\cos \omega t \Big]_{\theta_1}^{\theta_2} - MB_0 \Big[-\cos \omega t \Big]_{\theta_3}^{\theta_4}$$

$$2\pi L_{AV} = MB_0 \left(-\cos \theta_2 + \cos \theta_1 \right) + MB_0 \left(+\cos \theta_4 - \cos \theta_3 \right)$$

$$M = \frac{2\pi L_{AV}}{B_0 (\cos \theta_1 - \cos \theta_2 - \cos \theta_3 + \cos \theta_4)}$$

In the above analysis θ_1, θ_2, θ_3 and θ_4 are the threshold angles for torquer coil energization and L_{AV} is the average value of the pulsing input torque (also equal to the average value of the restraining torque of the torquemeter).

APPENDIX C

CHRONOLOGY OF EVENTS

INITIAL TESTS

Thursday, 22 August 1968

ISIS-A Spacecraft arrived at the magnetic test facility at 6:30 P.M.

Friday, 23 August 1968

Measured initial perm moment "as received".

Performed spacecraft exposure and deperm.

Established polarity of torque coil moment.

Monday, 26 August 1968

Measured magnetic field feedbacks from torque coils.

Measured and compensated probe bias.

Measured gating thresholds for x and y axes probes.

Tuesday, 27 August 1968

Re-aligned probe z-600.

Measured gating thresholds for z axis probes.

Calibrated z axis magnetometer probes in tip-over fixture.

Wednesday, 28 August 1968

Measured induced moment.

Measured stray field moment including solar simulation.

Calibrated x and y axes probes.

Measured perm of spacecraft tip-over dolly.

Prepared torquemeter for tests.

Thursday, 29 August 1968

Conducted torquemeter tests.

Friday, 30 August 1968

Recalibrated z axis probes using z artificial.

Made final check of spacecraft perm moment.

Spacecraft shipped out.

FINAL TESTS

Thursday, 21 November 1968

ISIS-A Spacecraft arrived at Magnetic Test Site.

Friday, 22 November 1968

Measured "as received" perm.

Conducted preliminary deperming.

Monday, 25 November 1968

Conducted final deperming.

Tuesday, 26 November 1968

Rechecked perm moment post ACS exercise.

Wednesday, 27 November 1968

Measured induced moment.

Rechecked spin-axis control system.

Made final check of perm moment.

Final probe calibration and bias measurements were made.